Spatial Coherence of Nonlinear, Nonstationary, Non-Gaussian Ocean Waves on a One-Mile Scale From Scanning Radar Altimeter

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LONG-TERM GOAL

The lack of good ocean surface data on the one-mile scale is a major stumbling block for proper evaluation of proposed Mobile Offshore Base (MOB) conceptual designs. A general model and associated software for stationary, linear, statistical, directional wave systems have been available for some time. If that model can appropriately be used for design of marine mega-structures, then there is no problem in proceeding with conceptual MOB designs and their evaluations. However, it is known that storm waves are nonlinear to some extent. The major goal is the determination of the accuracy of the linear approximation and the type of nonlinear feature present in severe storm waves.

OBJECTIVES

Many frustrations and uncertainties would disappear if adequate data on the proper spatial scale were available to serve as a basis for selection of design criteria. This project is designed to examine and analyze NASA scanning radar altimeter data collected by Ed Walsh.

APPROACH

Walsh has recorded SRA data in flights over storm wave systems near Australia and is in the process of collecting data for Atlantic storms (1998 and 1999 hurricane seasons). In the present project, these data are being analyzed and summarized graphically in a “design engineer’s atlas

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of storm wave measurements". The atlas includes various statistical studies that address the linear/nonlinear balance in severe storm waves.

WORK COMPLETED

The work this year consisted of developing methodology and algorithms, and related software. Pre-existing storm measurements and data from several Atlantic/Gulf of Mexico hurricanes were analyzed.

RESULTS

The work leading up to the VLFS'99 meeting in September 1999 encountered questions which needed resolution before the production of the final statistical Atlas of Storm Topography. In particular, methods were needed which did not interpolate to a regular grid and which allowed computations to be based on the actual measurements no matter how they were irregularly spaced over (x, y). This was important in order to guarantee that no local nonlinear features actually present in the sea surface were seriously reduced or even eliminated in the data processing. Some of the procedures previously used varied somewhat with the orientation of the regular grid which was tied to the flight direction. Consequently, this is also an artifact introduced by the analysis method, so it was desirable to find procedures that were insensitive to flight direction and which would work even if the airplane were flying "S" patterns or sharp turns within the data section being analyzed.

Two methods were selected for serious review. These were distorted quadrilaterals and Delaunay/ Voronoi tesselations (Ahuja and Schachter, 1983). The Delaunay/Voronoi approach was judged to have the most generality for data with irregular spacing, and conveniently, could be computed with functions DELAUNAY and VORONOI currently existing in MATLAB 5.3.

A tesselation is any family of disjoint 2-D patterns covering exhaustively a selected planar set. Let $\{x_i, y_i; i = 1, 2, \ldots, N\}$ be a set of locations on the plane. The ith Voronoi set is the set of all points in the plane which are closer to the (x_i, y_i)-location than to any of the other specified locations. This turns out to be the polygon formed by the perpendicular bisectors of the line segments from (x_i, y_i) to the other neighboring locations. An example of Voronoi polygons is given in Fig. 1. The red plus symbols are the generation locations, and each polygon surrounds those points which are closer to the enclosed location than to any other of the locations. The area of the Voronoi polygon is the natural value to assign to $dx\, dy$ in the numerical integration

$$I = \sum f\ (x_i, y_i)\ dx\ dy$$

over irregularly-located measurements. It allows a reasonable definition of a two dimensional finite Fourier transform over irregularly-spaced data.

The Delaunay triangulation consists of the triangles formed by the line segments perpendicular to the sides of the Voronoi polygons connecting the two locations which generated that side. The Delaunay triangles corresponding to the Voronoi polygons in Fig. 1 are shown in Fig. 2. (*Please note:* The Delaunay line segment may not physically intersect the polygon side which it is perpendicular to.)

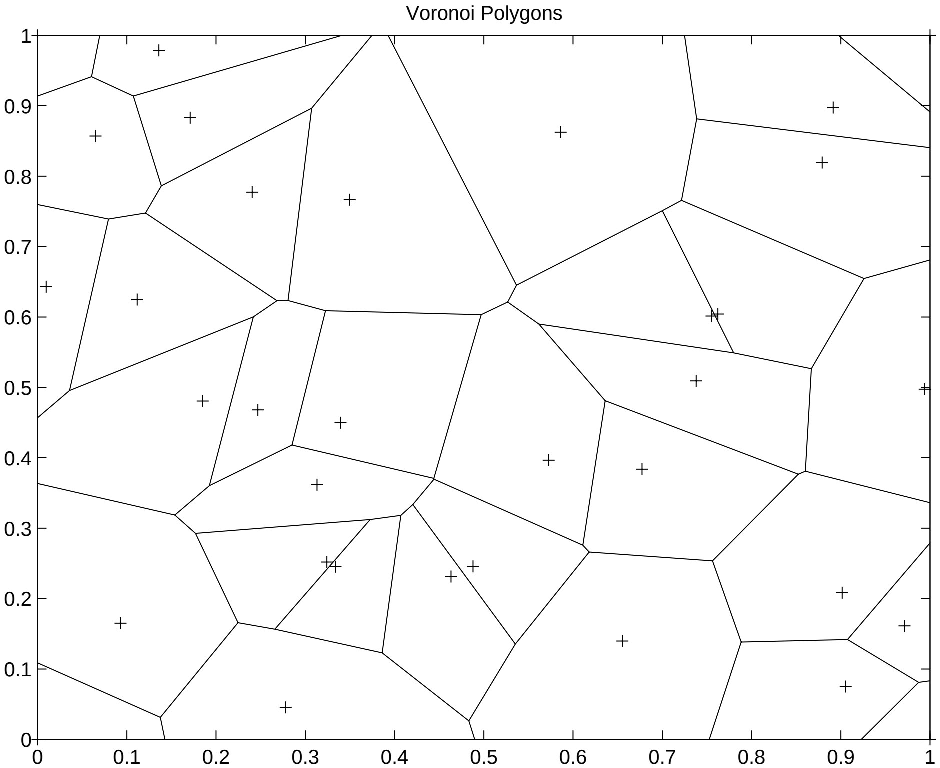

Figure 1: Voronoi Polygons

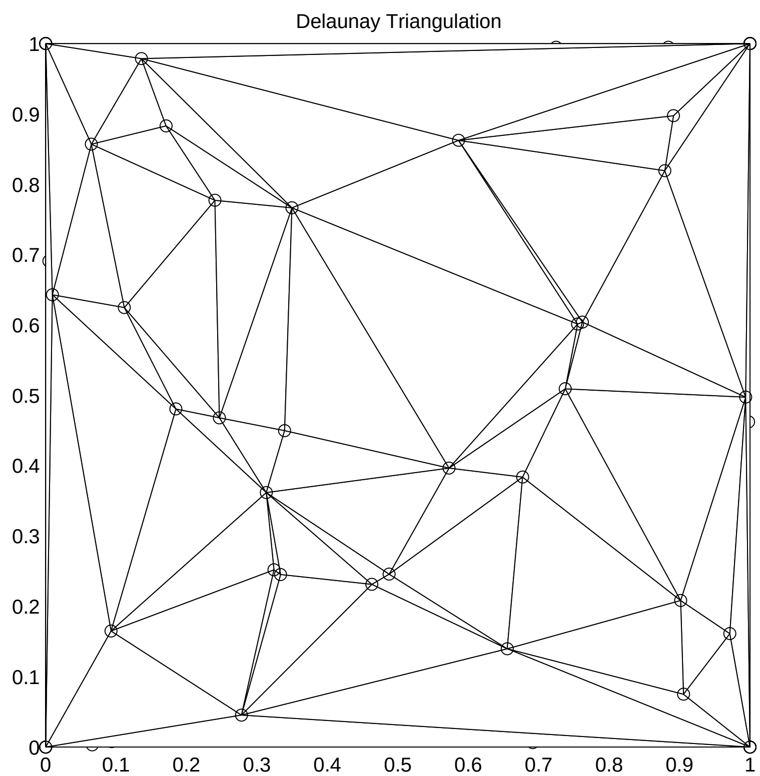

Figure 2: Delaunay Triangles

Each of the locations not on the convex hull of the set of locations is completely surrounded by Delaunay triangles and a set of radiating line segments which form the sides of the surrounding triangles that are connected to that location. The surrounding set of verticies connected to a specified location by a single Delaunay line segment will be called the *D*-neighborhood of order one, or primary *D*-neighborhood, for the selected locations. Similarly, the set of verticies not in the primary *D*-neighborhood and connected by two Delaunay line segments to the specified location will be called its secondary *D*-neighborhood, or *D*-neighborhood of order two. This concept can be extended to neighborhoods of order 3, 4, etc. in an expanding set of neighboring locations surrounding the reference locations.

There is a growing body of mathematical techniques built around nearest-neighbor concepts. Many of these are based on Euclidean distance or some other measure of distance, and the neighborhood of locations often end up all on one side of the reference location. The *D*-neighborhoods avoid this since they always surround the reference location if it is not on the convex hull.

In the study of the irregularly-spaced SRA data, the *D*-neighborhoods form a natural setting for the study of local nonlinearities. The elevations of each location are actual SRA measurements, so there is no distortion introduced by interpolation.

The Delaunay triangles can be used with splines to define the surface more precisely. In the work over the last several months cubic quadratic, and planar splines were examined as possible choices to use with the finite elements made up of the Delaunay triangles. This leads in a natural way to contouring routines for elevation based on the triangulation, and also contour maps of such sea surface properties as slope.

Since quadratic and cubic splines may introduce artifacts of analysis difficult to evaluate, it was decided to stick with the most simple case of planar finite elements, at least for the present. Thus on each Delaunay triangle, with vertices $\{x_i\, y_i\, z_i;\, i = 1, 2, 3\}$, the equation for the elevation is

$$z = A + Bx + Cy$$

with

$$\begin{aligned} z_1 &= A + Bx_1 + Cy_1 \\ z_2 &= A + Bx_2 + Cy_2 \\ z_3 &= A + Bx_3 + Cy_3 \end{aligned}$$

or

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix}.$$

The constants A, B, and C for that finite element may be solved for with

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{bmatrix}^{-1} \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}$$

providing the triangle is not degenerate.

Let (A_1, B_1, C_1) and (A_2, B_2, C_2) be the constants for two adjacent Delaunay triangles. Then the angle between them is given by

$$\cos\theta = \frac{B_1 B_2 + C_1 C_2}{\sqrt{\left(B_1^2 + C_1^2\right)\left(B_2^2 + C_2^2\right)}}.$$

A contour map of $\cos\theta$ should delineate crests and troughs fairly naturally, since this is where the change in slope is largest.

Another choice for locating the crest and trough lines is based on the Delaunay line segments. Each segment is common to two triangles. The slope of z perpendicular to the segment in each of the two triangles can be used to compute a directional change in slope perpendicular to the line segment. A line segment can be colored in a MATLAB figure according to the change of slope across that segment. A crest line would then be made up of the Delaunay segments with change from positive slope to negative slope across it. This appears very promising in the computations so far.

The two MATLAB functions, DELAUNAY and VORONOI, do not have supporting functions of the type needed in the SRA wave analysis. Consequently considerable time during the last few months have been devoted to the design and programming of a suite of functions for the operations on the Delaunay triangulation.

MATLAB code allows nested do-loops, but their use with large array computations eats up much computer time. Consequently, efficient processing of large data sets requires programs containing no do-loops, if at all possible. Sometimes it can't be avoided. However, usually with sufficient insight and ingenuity, do-loops can be avoided by working with matrix and array calculations. The work on this suite of computational functions is currently underway.

IMPACT/APPLICATION

To understand the very nonlinear rogue waves we must first record the conditions and patterns that produce them. How to obtain such data was a topic of considerable discussion at the September, 1999 VLFS meeting. These and subsequent discussions indicate that we should develop a mechanism for monitoring and recording form and conditions of the air-water interface in three dimensions and over a relatively long period of time. To this end, we have proposed a supplemental project (Marrs *et al.*, 2000) that will attempt to obtain rapid sequences of stereographic images from which sea-surface topographic data can be extracted via digital photogrammetry. The resulting data sets will provide 3-D representations of waves through a specified time period. We propose to record and analyze conditions prior to, during, and following the departure of wave patterns from linear behavior.

REFERENCES

Ahuja, N. and Schachter, B.J. (1983), *Pattern Models*, John Wiley & Sons, 301 pp.